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Energy dependent processing of fiber reinforced plastics with ultra short laser pulses

N. Schilling[a], A. Lasagni[a,b]*, U. Klotzbach[a]

[a]*Fraunhofer Institute of Material and Beam Technology, Winterbergstraße 28, 01277 Dresden, Germany*
[b] *Institute of Manafacturing Technology, Technical University of Dresden, Georg Bähr Straße 3c, 01069 Dresden, Germany*

Abstract

In this paper the processing of a fiber reinforced plastic consisting of glass fibers embedded in polypropylene with ultra short laser systems is shown. Focus of the study is on the dependence of working wavelength (1064 nm, 532 nm and 355 nm) and pulse duration (500 fs to 10 ps) on the laser ablation characteristic of the treated material. Depending on the energy density and the material properties, two different process regions could be identified.

Keywords: fiber reinforced plastics, ultra short laser processing, ablation characteristic

1. Motivation / State of the Art

Fiber reinforced plastics offers great potential for light construction, combined with high strength. The classical fields of fiber composites in polymeric matrix are the aircraft industry, here for airplane components, wings for wind energy turbines and sport articles since many years. Lately fiber reinforced plastics keep entering the automotive and mechanical engineering market more and more. In these markets the traditional hand maid production chain for low batch sizes has to be changed to flexible semi automated and full automated production processes. For amortizing the invest costs for machines and therefore the resulting price of fiber reinforced components, the production machines have to show high flexibility in contour and high throughput potential [1].

* Corresponding author. Tel.: +49 351 83391 3007
E-mail address: andres-fabian.lasagni@iws.fraunhofer.de

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One possibility to raise throughput is the usage of thermoplastic matrices containing glass fiber and carbon fiber as reinforcing material. By using thermoplastics it is not necessary to produce components in there final contour like it is needed by using epoxy matrices. In the case of thermoplastic material so called organo sheets can be used which get there final contour through reforming process and joining with other thermoplastic components. The joining with additional components can be done for example by inkjet molding or laser welding.

For realizing a laser based production chain for thermoplastic reinforced materials different processing methods are needed. With pointing up the interaction behavior between the composite material and the laser beam the parameter range for different process like surface activation, surface structuring, cutting, drilling and other can be cleared.

The established method of laser cutting for example uses both CO_2 lasers and Nd:YAG lasers. These systems can be also used to process fiber reinforced composites in nearly in the same way like cutting metals [2]. Like mechanical processing, treatment with lasers has to handle with the same material changing conditions between fiber and matrix. Particularly absorption, ablation threshold and heat conductivity are the most important variables influencing the machinability of fiber reinforced composite materials. For example the high heat conductivity of carbon fibers with 50 W/mK [3] compared to epoxy resin with 0.2 W/mK [3] makes a precise treatment difficult. Local contributed energy for sublimating material is directed away through carbon fibers as heat. In neighbor regions this heat damages the polymeric matrix and reduces the bonding strength between fiber and matrix. As a result, short interaction times between the material and the laser beam are needed to realize a defect-poor processing [5, 6]. Shortening the interaction time can be achieved for continuous wave (cw) laser by increasing the scan speeding processes such like remote cutting, or by using pulsed lasers. In particular, ultra short pulsed laser systems offer the shortest interaction time between material and laser beam in the region of tens of picoseconds down to hundreds of femtoseconds.

In this study, processing of fiber reinforced polymer consisting of glass fibers embedded in polypropylene (PP) using ultra short pulsed laser systems is shown. The dependence of working wavelength (1064 nm, 532 nm and 355 nm) and pulse duration (from 500 fs to 10 ps) on the laser ablation characteristic of the treated material is shown.

2. Experimental

2.1. Material

Glass fibers (GF) are the reinforcement agent most used in polypropylene (PP) based composites, as they have a good balance between properties and costs [4]. As substrate a 2 mm thick sheet PP with reinforced with unidirectional glass fibers with a fiber content of 60% was utilized. The glass fiber diameter varies between 15 and 20 µm.

2.2. Experimental Setup

Two laser systems with pulse durations in the fs and ps regime were utilized for the ablation experiments. The first laser is a Fuego System from the company Time-Bandwidth (Switzerland) with a fixed pulse duration of 10 ps. The fundamental wavelength is 1064 nm with maximal pulse energy of 150 µJ at 200 kHz. The second system belongs to the “scientific series” of the company Active Fiber Systems GmbH from Jena (Germany). This laser offers the possibility to vary the pulse duration between 500 fs up to 20 ps. The fundamental wavelength is 1030 nm. Both systems are featured with frequency conversion modules for second and third harmonic generation. The beam deflection was realized by intelliScan systems from Scanlab (Germany). For this study the basic wavelength, second and third harmonic are compared. The spot diameter was varied from 30 µm to 60 µm. For the ablation experiments square areas of 3 to 5 mm² were processed. The squares were filled with simple lines perpendicular to the fiber direction. Depending on the used laser source and wavelength the pulse overlap and the line separation was varied between 25% up to 100% of spot diameter. The spot for IR-wavelength was measured with 60 µm in diameter, for green-wavelength 33 µm and for UV-wavelength 25 µm. For the experiments the energy density was varied between 0.025 J/cm² and 5.02 J/cm².

2.3. Surface Characterization

Surface characterization of the treated materials was realized with a Keyence digital microscope VHX-2000, a Leica DCM 3D white light intferometer and a probe indicator from Mitutoyo Corp. The characterization included damages in the not treated area besides the processing location, damages at the fibers at energy densities were the fiber itself should not be influenced, the homogeneity of the ablation and the ablation rate. As indicator for selective and homogenous ablation region profile measurements were realized. For the selective ablation region it was also necessary to characterize the damage behavior of the fibers by optical microscopy.

3. Results and Discussion

Firstly the influence of both wavelength and pulse duration on the heat affected zone produced by the laser treatment was investigated. The energy density was varied between 0.05 and 5.02 J/cm². Independently of the utilized laser wavelength, very thin heat affected zone of 10 µm near to the ablation area were measured. As example, damaged areas of the glass-reinforced PP-composite treated with fluences of 2.8 J/cm² for IR and 5.0 J/cm² for green and pulse durations of 10 ps and 500 fs are shown in Fig. 1 a , b, c, d, respectively. The heat affected areas for the ps processing were slightly larger with 10.06 (Fig. 1a) and 7.35 µm (Fig. 1c) than for the fs processing with sizes of 5.62 µm (Fig. 1b) and 4.85 µm (Fig. 1d), for IR and green, respectively.

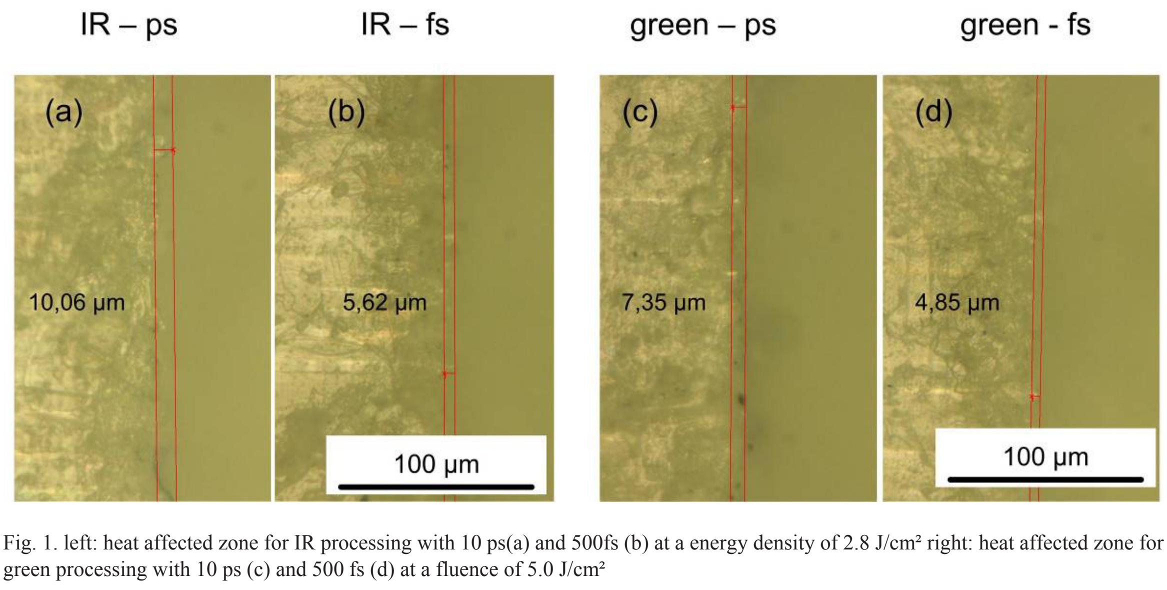

Fig. 1. left: heat affected zone for IR processing with 10 ps(a) and 500fs (b) at a energy density of 2.8 J/cm² right: heat affected zone for green processing with 10 ps (c) and 500 fs (d) at a fluence of 5.0 J/cm²

Secondly, the ablation behavior in both fs and ps regime was studied using the three different laser wavelengths. Two main ablation behaviors were observed depending on the laser wavelength, independently of the pulse duration. These were identified by optical inspection and measurement of the ablation rate.

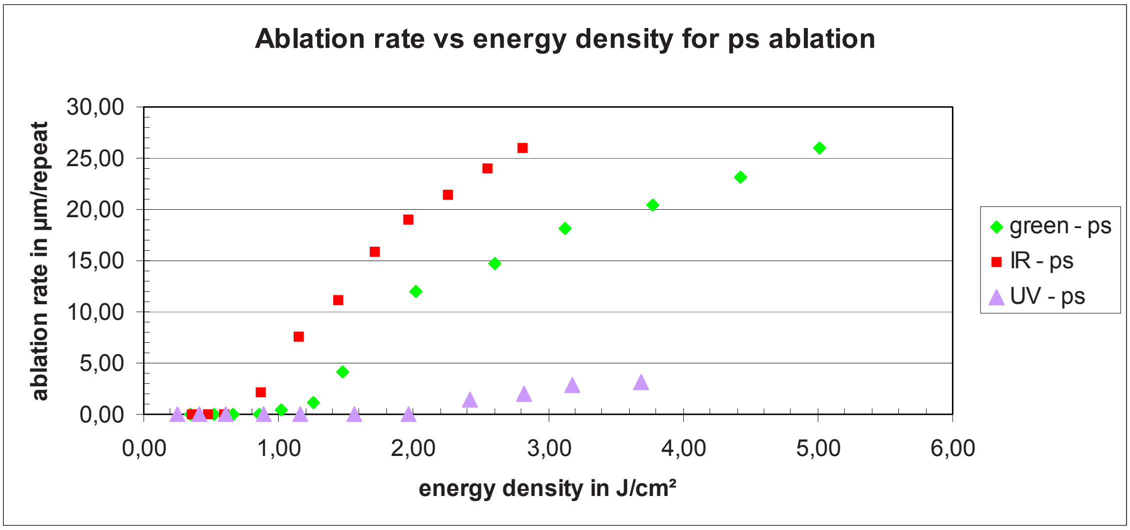

Fig. 2. Ablation rate versus energy density in ps-processing regime. Pulse separation for the experiments was 25%.

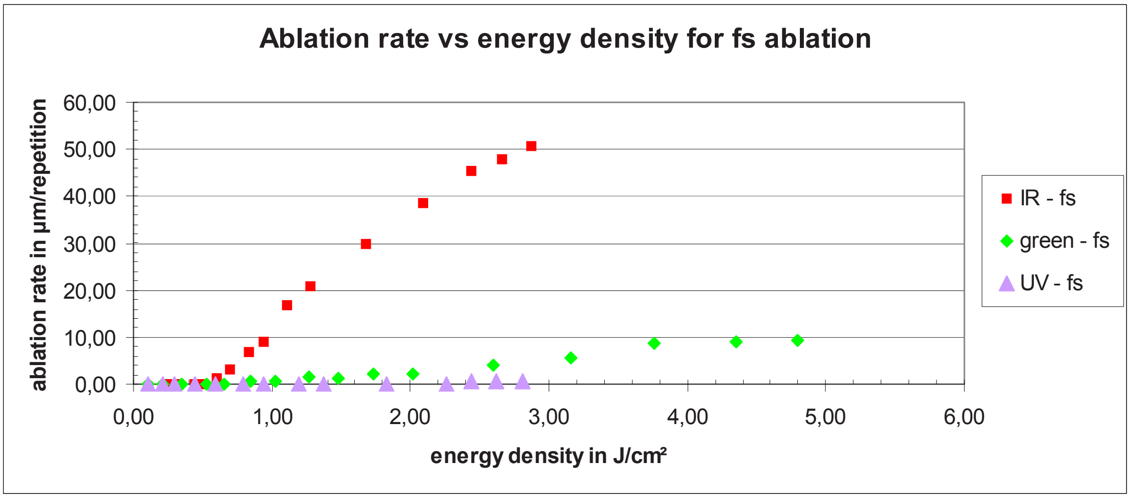

Fig. 3. Ablation rate versus energy density in fs-processing regime. Pulse separation for the experiments was 25%.

For UV and green processing laser wavelengths and for pulse separations larger than 50%, after exceeding the ablation threshold of the matrix material, a processing range where only the matrix is ablated and the fibers remains with minimal visual perceptible damage was observed. The measured ablation rate in this energy density range (see Fig. 2 and 3) is below 1 µm/repetition depending on the thickness of the polymer matrix covering the glass fibers. Furthermore, for UV- fs processing this behavior was observed over the whole studied energy density range (see Fig. 3). For UV-ps ablation, an energy density of 2 J/cm² determines the end of this ablation behavior. For the green processing, an energy density of 1 J/cm² was enough to induce damage of the fibers for both ps- and fs-processing. For IR-processing, this parameter window could not be identified. These regimes are summarized in Table 1 for all pulse durations and wavelengths utilized.

	Wavelength (nm)	Pulse duration (ps)	Pulse Separation (%)	Laser fluence range (J/cm²)
Ablation regime 1	355	10	50 - 100	0.4 – 1.9
	343	0.5	50 - 100	0.2 – 2.8
	532	10	50 - 100	0.5 – 1.0
	515	0.5	50 - 100	0.2 – 1.0
Ablation regime 2	355	10	25 – 100	2.4 – 3.7
	532	10	25 – 100	1.3 – 5.0
	515	0.5	25 – 100	1.3 – 5.0
	1064	10	25 – 100	0.9 – 2.8
	1030	0.5	25 – 100	0.6 – 2.8

Table 1. Overview of laser fluence ranges for selective ablation of the polymer matrix without damage of glass fibers (regime 1) and with damage of the fibers (regime 2) as function of pulse duration and laser wavelength.

On the other hand, for pulse separations below 25% (10 µm) at constant energy densities, darkening and damage of the fibers was induced (see for example Fig. 4d). This effect was observed for all wavelengths and pulse durations. A possible explanation for this behavior can be given by incubation effects [9] in the fiber material structure, especially at the central region of the laser beam with the highest the highest energy density in the Gaussian distribution. Using high pulse overlaps, the number of cumulative effects, and therefore the changes in the material structure that are produced, can lead after a certain number of repetitions to a macroscopic visible damage of the fiber structure. This behavior is summarized in Fig. 4 for a 355 nm laser wavelength with pulse duration of 10 ps and a laser fluence of 1.57 J/cm². At pulse separation between 50% (Fig. 4c) and 100% (Fig. 4a) small modifications on the fibers could be observed. On the other hand, at 25% of pulse separation (Fig. 4d) the fibers were damaged.

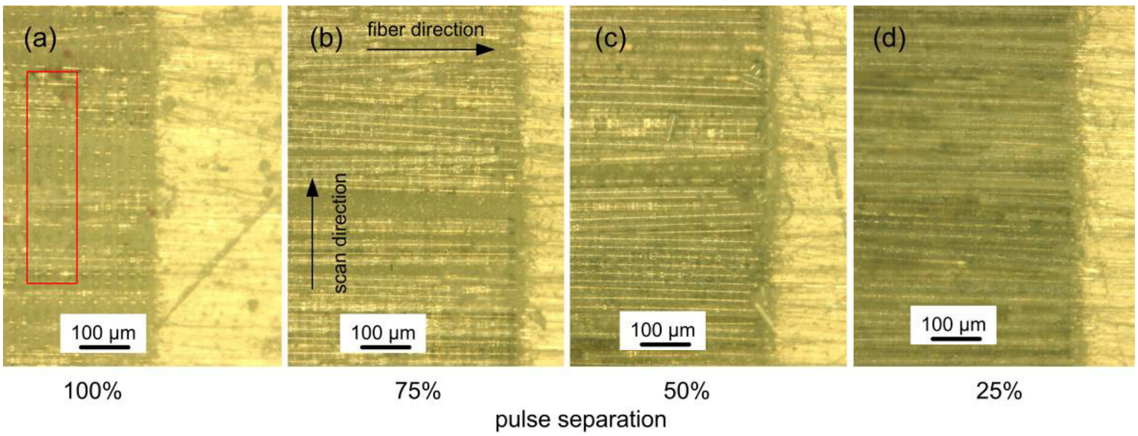

Fig. 4. Damage accumulation effect during the matrix ablation in dependence of the pulse separation. The working wavelength was 355 nm, pulse duration 10 ps and laser fluence was 1.57 J/cm². In the red corner remaining parts of the matrix can be seen.

The second ablation behavior is characterized by a combined ablation of polymer matrix and glass fibers. This behavior could be observed for all 3 working wavelengths (see Table 1). Furthermore, for low energy densities within this ablation behavior, fragments of glass fibers in the size of 50 µm to 100 µm could be also observed. With increasing the pulse energy, a higher ablation of the glass fibers is observed and therefore showing a more homogenous ablation. This effect can be enhanced by minimizing the pulse separation which leads to a higher damage density as shown in Fig. 4d and thus with a higher ablation rate of the glass fibers. The highest ablation rates were achieved by processing with a pulse separation of 25% (see Fig. 2 and 3).

For the UV wavelength, only in ps processing both material ablation of the matrix and fibers could be measured. In the density range between 2.4 J/cm² to 3.7 J/cm² the ablation rate grows up to 3.2 µm per repetition. For the green wavelength. the simultaneous ablation of the matrix and fibers (second ablation behavior) starts at an energy density of 1.3 J/cm² for both ps- and fs-processing. In the ps- regime, the ablation rate grows up on 26 µm/repetition, while for fs-processing an ablation rate of only 9.33 µm/repetition. The highest ablation rates were measured in the IR-processing. For ps-processing the material ablation starts at an energy density of 0.86 J/cm² and increases up to 26 µm/repetition at an energy density of 2.8 J/cm². For fs-processing the material ablation starts at a fluence of 0.6 J/cm² with an ablation rate up to 50.7 µm/repetition at 2.8 J/cm² (see Fig. 2 and 3). The results of high ablation rates can be explained with the increasing of fluence in high fluence regimes [7, 8].

An example of the 3D-surface topography of the laser treated area showing the ablation of the PP matrix is depicted in Fig. 5. The ablation depth at the areas corresponding to the matrix material was between 20 to 25 µm. These values were observed for both ablation regimes, and correlates well with the diameter of the glass fibers (between 15 µm and 20µm). This observation indicates that before ablating a layer of fibers, the polymer matrix surrounding the fibers is always first ablated.

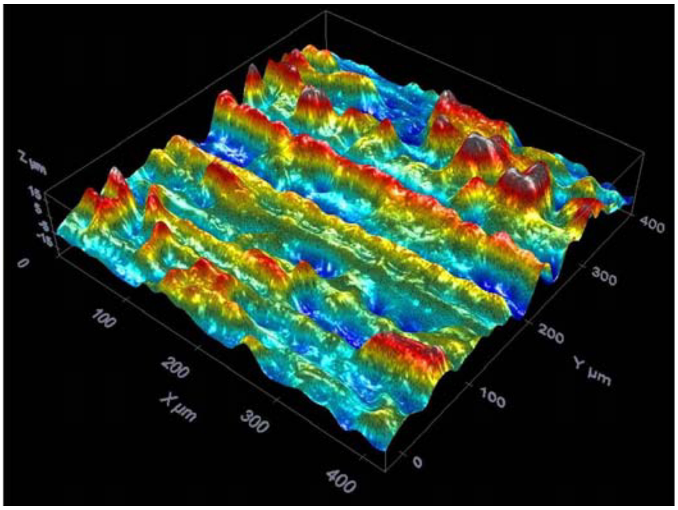

Fig. 5. roughness measurement for fs-IR processing with 25% pulse separation at an energy density of 2.8 J/cm².

4. Conclusion

In the study, the dependence of different working wavelength, pulse duration and energy densities on the ablation behavior of glass fiber reinforced polypropylene was shown. Two differently ablation behaviors were observed depending only on the used wavelengths. For UV and green wavelengths both regimes, selective ablation of the PP matrix, and ablation of the matrix and fiber, were observed. For IR radiation, only the simultaneous ablation of the fibers and matrix could be shown. On the other hand, the pulse duration strongly influenced the ablation rate. For IR wavelengths, the ablation rate for fs pulses was significantly higher (approximately 2 times) than for ps pulses. Contrary, for green wavelength the observed ablation rate was higher for the ps pulses. Finally, for UV radiation, only by using ps pulses the processed material was ablated. The here reported results are usable to estimate reachable process parameters for different laser based applications including cutting, joining preparation, drilling or sensor integration.

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